Technical Memorandum

To: Rebecca Chu – US EPA Region X RPM

From: Kristen Kerns, David Clark – US Army Corps of Engineers, Seattle District

Project: Jorgen Forge Early Action Area Removal Action

Subject: Breakthrough Analysis of the Removal Action Boundary Backfill

Date: September 13, 2016

1.0 Overview

In order to meet the removal action objectives, EPA's Action Memorandum (2011) required complete excavation of the bank and dredging of sediment within the site that exceeded the Removal Action Levels (RvALs) for the Contaminants of Concern (COCs). However, data from the post dredge surface, also called the Z-layer, finds PCBs levels in the in-waterway sediments above the RvAL of 12 mg/kg OC (130 μg/kg dw) for total PCBs (as Aroclors). Because PCBs exist in the sediments of the site above the PCB RvAL, EPA is now evaluating the backfill material placed within the RAB for its ability to function as an isolation barrier for the contamination remaining at depth. Because the original intent of the backfill placement was simply to restore the site to pre-dredge elevations, the composition and thickness of the backfill material was not selected, or designed to, serve as an isolation barrier.

The purpose of this technical memorandum is to summarize the findings of the breakthrough analysis of the Removal Action Boundary (RAB) backfill at the Jorgen Forge Early Action Area. The breakthrough analysis was performed to achieve several objectives. First, the analysis assesses the risk of PCB contaminated sediments within the z-layer of the RAB migrating upwards through the backfill material over time. The analysis considers this migration occurring under non-steady state conditions over two time intervals: 50 years and 100 years. Non-steady state conditions assume equilibrium has not been reached and instead evaluates conditions on a temporal scale. In contrast, steady state assumes equilibrium has been reach and does not account for processes as a function of time.

The analysis also evaluates whether the existing backfill material adequately isolates the PCB contaminated sediments such that the RvAL of 12 mg/kg OC (130 μg/kg dw) for PCBs is attained within the backfill surface of the RAB. The analysis evaluates breakthrough in to the top 10 cm and top 45 cm of backfill material. The analysis includes a focused sensitivity analysis of different backfill thicknesses, which is described in greater detail in Section 2.2.

2.0 Data Set Used for Analysis

2.1 PCB Sediment Samples

As part of the development of the Removal Design documents, EMJ was required to identify sampling locations of the post-dredge surface to assess the amount of PCB contamination in the "z-layer" sediments of the site. The removal design of the in-waterway portion of the site divided in to 5 distinct

“Dredge Management Units”, or DMUs. Sampling locations were identified within each of these DMUs to represent the post-dredge surface.

After several rounds of review, EMJ chose, and EPA approved, 7 sampling locations within these DMUs to represent the in-water sediment surface, post dredge, of the in-waterway portion of the site. EMJ chose 2 sampling locations for DMU 5 & DMU 3; and one sampling location for the remaining DMUs (1, 2, & 4). Because these sampling locations are intended to be representative of the post dredge sediment surface on a larger scale; the PCB contamination at each of the sampling locations represents the concentration of PCBs for the entire DMU. However, for the purposes of characterizing the site and determining the potential for backfill at the site to provide an adequate isolation barrier: these seven samples may under represent the site given the natural heterogeneity of sediments. If further assessment of the backfill to function as an isolation barrier were to occur, it is recommended that a conservative approach to the analysis be used given the existing sample density and heterogeneity of the site. Additional sampling could also be conducted to ensure better characterization.

While the sample locations themselves are fixed within each of the DMUs: there are multiple data sets available for each sample location. Specifically, three sets of sampling data were reviewed for this analysis:

- 2014 z-layer sediment sample results collected post-dredge and prior to backfill placement;
- 2016 z-layer sediment sample results collected by sonic drilling through the backfill material to the underlying sediment surface; and
- EPA’s split sample results of the 2016 z-layer sediment sample analyzed by EPA.

All three sets of sampling data were analyzed as part of the modeling effort. Results presented in Tables 1 and 2 only present the highest PCB sediment concentration at each sampling location. Choosing the samples with the highest PCB sediment concentrations is a conservative approach which takes into account the heterogenity of PCB concentrations across the site. In comparing PCB sediment concentrations across the site that have been collected over the years, the site demonstrates high heterogeneity throughout the RAB. In consideration of this situation, we utilized the highest PCB concentrations to provide modeling projections that considered the worst factual scenarios in order to be protective of human health and the environment. Model outputs for all samples are concurrently being provided to EPA in electronic format.

2.2 Backfill Thickness

While the PCB concentration within each DMU is represented by a sampling data point as a constant, the thickness of backfill across each DMU varies. This is because the dredge depths varied within each of the DMUs, and consequently the amount of backfill placed across each DMU to bring the site back up to pre-dredge characteristic varies. The Corps of Engineers reviewed the as-built information provided by EMJ as part of the draft Pre-Final Construction Completion Inspection Report materials. Evaluation of the as-built information, as well as observations recorded during the February 2016 sampling event performed by EMJ, indicates that placed backfill depths of <2 ft. may exist within portions of the site.

To assess this variable, a focused sensitivity analysis of different levels of backfill thickness across each DMU was performed to consider breakthrough risk for different depths of backfill across each DMU. As stated in the prior section of this memorandum (Section 2.1) each of the site-specific sample locations were chosen to be ‘representative’ of the leave surface for a broader area as part of the EPA-approved

Removal Design documents. The focused sensitivity analysis of backfill thickness therefore evaluated breakthrough of the existing backfill material at thicknesses of approximately 1, 2, 3, and 4ft (30, 60, 90, and 120cm). These intervals were chosen based on estimated backfill thicknesses of the as-built drawings provided by EMJ; as well as field observations of backfill cover during the February 2016 sampling event. EPA and the Corps have observed that there are discrepancies between the reported backfill depth, especially in the area nearest the navigation channel, and the observed backfill depths from the February 2016 sampling event. It is possible that no backfill exists along the edge of the RAB closest to the navigation channel. Therefore, the sensitivity analysis includes an interval of 1 foot.

For those sample locations where the RvAL was not achieved in the average top 45cm in the focused sensitivity analysis of approximately 1, 2, 3, and 4ft (30, 60, 90, and 120cm), greater hypothetical thickness were evaluated to determine how much backfill would be required in order to meet the RvAL.

Characteristics of the backfill material itself were derived from the available information from the Site, including the most recent sampling event performed in February 2016 that specifically evaluated the backfill material. Several assumptions were also applied from adjacent sites with similar characteristics. Greater detail about these assumptions can be found in Section 5.0 of this document, entitled "Assumptions and Limitations". Of note is both the variability in- and significance of- TOC within the Site. The breakthrough analysis shows that the amount of TOC within the backfill material greatly impacts the likelihood and extent of breakthrough of the current backfill material at the site. As PCB contaminated porewater migrates upward through the backfill, it will incur some residence time with the recently added carbon that has been placed at the site in the backfill material. This carbon, in the form of TOC, will absorb some of the dissolved phase PCBs in the porewater during the process of upward migration. The more TOC present in the backfill, the more absorption will occur. In addition, higher TOC content in the Z-layer sediment will result in less PCBs present in the porewater, remaining bound to carbon in the native sediment, and thus less available for upward transport through the backfill. For TOC content in the native sediment, TOC varied from 0.05 to 1.2 % in the 0 to 1 ft interval, based on the 2016 sampling results. For the backfill material, TOC content ranged between 0.031 and 1.12 in the 0 to 1 ft interval, based on the 2016 sampling results.

3.0 Methods

For this effort, the Model for Chemical Containment by a Cap (version 1.19 dated June 8, 2012) by Dr. Danny Reible of the University of Texas was used to estimate the maximum total PCB (as Aroclors) dry weight concentrations in the top 10cm and 45cm of backfill for seven different sample locations within the RAB assuming steady state and non-steady state conditions. The model was also used to estimate risk of breakthrough at different backfill depths by performing a sensitivity analysis that accounts for the variability of backfill material across the site in increments of 1, 2, 3, and 4 ft (30, 60, 90 and 120 cm). For those sample locations where the RvAL was not achieved in the average top 45cm in the focused sensitivity analysis of approximately 1, 2, 3, and 4ft (30, 60, 90, and 120cm), greater hypothetical thickness were evaluated to determine how much backfill would be required in order to meet the RvAL. This memorandum also documents assumptions and limitations of the model (Section 5.0), and a recommendation from USACE regarding interpretation of the results.

Methods for this modeling effort was conducted in accordance with the Quality Assurance Project Plan (QAPP), dated August 15, 2016. The QAPP is attached to this Memorandum as Appendix A.

There were no deviations from the methodology outlined in the QAPP.

4.0 Results

Tables 1 and 2 summarize the results of the focused sensitivity analysis of varying backfill thicknesses ranging from approximately 1 to 4 ft (30 to 120 cm). Additional depths were also analyzed for PDS 1, 2, 3, 5, and 7 to show hypothetical depth of backfill required in order to achieve an average total PCB concentration less than the site RvAL in the top 45cm. Table 1 provides model results for non-steady state conditions at 50 years post construction. Table 2 provides model results for non-steady state conditions at 100 years post construction. As explained in Section 1.0, non-steady state conditions assume equilibrium has not been reached and instead evaluates conditions on a temporal scale. In contrast, steady state assumes equilibrium has been reach and does not account for processes as a function of time. Tables 1 and 2 only present the model results for the sample with the highest sediment concentration within each DMU and the coffer dam. The basis for using the highest PCB concentration data is described in Section 2.1. These tables display modeling results for estimated breakthrough at a series of increments depths from surface of backfill, including the top 10cm and top 45cm of backfill material for each DMU.

Raw data outputs generated in Microsoft Excel for all model runs are being provided concurrently to EPA in electronic format.

Table 1. Predicted Total PCB Concentrations 50 years Post Construction for Backfill Thickness Sensitivity Analysis

	PDS -1 (2014)					PDS-2 (2014)					PDS-3 (2014)					PDS-4 (2014)				PDS-5 (2016)					PDS-6 (2014)				PDS-7 (2016)				
DMU	**DMU 5**					**DMU 4**					**DMU 3**					**DMU 2**				**DMU 3**					**DMU 1**				**coffer dam**				
Total Organic Carbon (%) in Backfill (0-60cm)	**0.031**					**0.062**					**0.092**					**1.12**				**0.104**					**0.202**				**0.031**				
Total Organic Carbon (%) in Z-Layer (0-1ft)	**0.93**					**0.694**					**0.659**					**1.64**				**0.818**					**0.841**				**0.05**				
Concentration Measured in Z-Layer (0-1ft)	**1560**					**252**					**960**					**760**				**2830**					**198**				**2200**				
Sensitivity Analysis of Backfill Thickness (cm)	30	60	90	120	330	30	60	90	120	150	30	60	90	120	150	30	60	90	120	30	60	90	120	150	30	60	90	120	30	60	90	120	360
Modeled Non-Steady State Backfill Concentration at 50 Years Post Construction (ug/kg dw)																																	
Approx. depth from surface of backfill (cm)																																	
0	1560	1468	959	418	0	236	69	7	0	0	605	30	1	0	0	0	0	0	0	1370	33	0	0	0	4	0	0	0	2200	2070	1352	2074	0
4	1560	1489	1050			245	85	11			753	48	1			0	0	0		1899	59	1			15	0	0		2200	2100	1481		
8	1560	1520	1136	516		249	120	18	1	0	858	109	3	0	0	0	0	0	0	2333	164	2	0	0	44	0	0	0	2200	2144	1602	2104	
11	1560	1531		623		251	138		2		903	155		0		0	0		0	2538	255		0		75	0		0	2200	2159		2128	
15	1560	1539	1214		0	251	156	26		0	931	212	6		0	0	0	0		2675	379	6		0	110	0	0		2200	2170	1712		
19	1560	1545	1283	735		252	173	38	4		952	280	13	0		5	0	0	0	2782	540	14	0		159	1	0	0	2200	2179	1810	2147	0
23	1560	1553	1343	849		252	202	52	7	1	958	439	26	1	0	145	0	0	0	2820	970	31	1	0	187	4	0	0	2200	2190	1894	2161	
27	1560	1555	1394			252	214	70			960	525	46			472	0	0		2828	1226	63			195	8	0		2200	2193	1966		
30	1560	1557	1436	962		252	224	90	13	1	960	609	79	2	0	760	0	0	0	2830	1495	120	2	0	198	15	0	0	2200	2196	2025	2172	
34	native sediment	1558	1469	1068	0	native sediment	232	112	21		native sediment	687	126	6		native sediment	0	0	0	native sediment	1762	214	6		native sediment	26	0	0	native sediment	2197	2072	2180	
38		1559					243			3		816			0		0				2234			0		65				2199			0
42		1560	1496	1167			246	135	33			863	190	14			0	0	0		2420	357	16			91	0	0		2199	2109	2187	
46		1560	1515	1254			249	157	49	6		899	272	29	1		2	0	0		2565	556	38	0		118	1	0		2200	2137	2191	
Average concentration over ~45cm interval	**1560**	**1538**	**1300**	**844**	**0**	**250**	**181**	**65**	**14**	**2**	**902**	**436**	**69**	**6**	**0**	**340**	**0**	**0**	**0**	**2569**	**1085**	**124**	**7**	**0**	**137**	**25**	**0**	**0**	**2200**	**2169**	**1833**	**2149**	**0**

Indicates exceedence of the Jorgensen RvAL (12 mg/kg OC; 130 ug/kg dw)

Table 2. Predicted Total PCB Concentrations 100 years Post Construction for Backfill Thickness Sensitivity Analysis

	PDS -1 (2014)					PDS-2 (2014)					PDS-3 (2014)					PDS-4 (2014)				PDS-5 (2016)					PDS-6 (2014)				PDS-7 (2016)				
DMU	**DMU 5**					**DMU 4**					**DMU 3**					**DMU 2**				**DMU 3**					**DMU 1**				**coffer dam**				
Total Organic Carbon (%) in Backfill (0-60cm)	**0.031**					**0.062**					**0.092**					**1.12**				**0.104**					**0.202**				**0.031**				
Total Organic Carbon (%) in Z-layer (0-1ft)	**0.93**					**0.694**					**0.659**					**1.64**				**0.818**					**0.841**				**0.05**				
Concentration Measured in Z-Layer (0-1ft)	**1560**					**252**					**960**					**760**				**2830**					**198**				**2200**				
Sensitivity Analysis of Backfill Thickness (cm)	30	60	90	120	330	30	60	90	120	150	30	60	90	120	150	30	60	90	120	30	60	90	120	150	30	60	90	120	30	60	90	120	360
Approx. depth from surface of backfill (cm)	**Modeled Non-Steady State Backfill Concentration at 100 Years Post Construction (ug/kg dw)**																																
0	1560	1560	1551	1471	74	252	237	155	68	23	954	604	164	28	4	0	0	0	0	2777	1357	254	30	3	103	3	0	0	2200	2200	2187	2074	55
4	1560	1560	1553			252	241	170			958	659	215			0	0	0		2809	1543	360			139	5	0		2200	2200	2191		
8	1560	1560	1555	1492		252	246	184	84	32	959	756	274	45	8	0	0	0	0	2822	1901	493	55	7	167	14	0	0	2200	2200	2193	2104	
11	1560	1560		1509		252	247		101		960	797		70		1	0		0	2826	2064		94		180	21		0	2200	2200		2128	
15	1560	1560	1557		114	252	249	196		44	960	832	339		15	11	0	0		2828	2212	655		15	189	30	1		2200	2200	2195		
19	1560	1560	1558	1522		252	250	207	119		960	862	410	105		113	0	0	0	2830	2343	843	155		195	42	1	0	2200	2200	2197	2147	91
23	1560	1560	1558	1532		252	251	217	138	59	960	906	483	150	27	423	0	0	0	2830	2549	1053	243	30	197	73	3	0	2200	2200	2198	2161	
27	1560	1560	1559			252	251	225			960	922	557			646	0	0		2830	2625	1279			198	91	5		2200	2200	2198		
30	1560	1560	1559	1540		252	252	232	156	76	960	933	628	207	46	760	0	0	0	2830	2684	1512	365	59	198	110	10	0	2200	2200	2199	2172	
34	native sediment	1560	1560	1546	169	native sediment	252	237	173		native sediment	942	695	275		native sediment	0	0	0	native sediment	2730	1741	525		native sediment	128	17	1	native sediment	2200	2199	2180	144
38		1560					252			95		953			74		4				2787			107		159				2200			
42		1560	1560	1550			252	242	189			956	754	352			16	0	0		2804	1959	724			172	28	1		2200	2200	2187	
46		1560	1560	1554			252	245	203	115		957	805	436	116		53	0	0		2814	2157	957	184		181	43	3		2200	2200	2191	
Average concentration over 45cm interval	**1560**	**1560**	**1557**	**1524**	**119**	**252**	**248**	**210**	**137**	**63**	**959**	**852**	**484**	**185**	**41**	**384**	**6**	**0**	**0**	**2823**	**2340**	**1119**	**350**	**58**	**181**	**79**	**10**	**1**	**2200**	**2200**	**2196**	**2149**	**97**

Indicates exceedence of the Jorgensen RvAL (12 mg/kg OC; 130 ug/kg dw)

5.0 Assumptions and Limitations

There are several assumptions and limitations associated with the modeling effort.

Representativeness of the PCB concentrations across the Site. Given the nature of the model, a PCB source equivalent to the highest post-dredge PCB sample concentration in the z-layer was assumed throughout each DMU. This approach accounts for the heterogeneity of PCB concentrations within the RAB. Given an uncertainty around the representativeness of the data for the entire site (i.e., the extrapolation of sampling data from a single location could result in either an over or under estimate of the PCB concentrations within each DMU); a conservative approach relying on the highest known concentration of PCBs, and assuming that this concentration exists throughout the DMU, was taken to ensure that the analysis provides an estimate of breakthrough risk that favors being protect human health and the environment based on a worst case scenario from the existing data set.

PCB Concentration in Porewater. The model requires the PCB concentration in the Z-layer to be input as a porewater concentration. Given that all data collected in the 2014 and 2016 sample efforts were bulk sediment, a mathematical conversion to a porewater concentration was performed assuming $C_0 = C_{sed}/(F_{oc}*K_{oc})$. This calculation is generally an oversimplification of the sediment-porewater relationship since the presence of differing PCB congeners and type of organic carbon can heavily influence the overall partitioning of PCBs into porewater.

Porosity of Backfill Material across the Site. Given that no site specific data was available to characterize the porosity of backfill material at the site, values for this parameter was derived from adjacent sites, specifically Terminal 117 and Slip 4, where isolation caps for PCBs are constructed. However, due to the coarse nature of the backfill material at the Jorgensen Forge Early Action Area, there is likely to be large interstitial spacing, minimal cohesiveness, and low organic carbon content at the site. This differs from Terminal 117 and Slip 4, where a more sand-like material was used. This difference almost certainly results in an overestimation of the protective functionality of backfill at the site.

Percent Total Organic Carbon within the Backfill at the Site. The percent total organic carbon (TOC) in the backfill at each sample station is based on the 0-60 cm sample interval from the surface of the backfill taken as part of the EMJ 2016 sampling effort. This assumes that the 0-60 cm interval is representative of the TOC value throughout the vertical and horizontal extent of the backfill, which may be either an under- or over- estimation that could impact the overall predictions of the model. TOC measurements for the backfill were not collected by EMJ in 2014, as required by the OMMP for characterization of baseline conditions. Lack of this data furthers the uncertainty in the widely variable TOC content for the backfill. Further, per the Remedial Action Work Plan (May 2014), granular activated carbon was added to the backfill material in the vicinity of PDS-7 at a concentration of 0.5 percent granular activated carbon by weight. However, there is no 0-60 cm sample of the backfill in the immediate vicinity of PDS-7 to confirm the application or amount of activated carbon within this location. For the focused sensitivity analysis of backfill thickness, the TOC measured in the backfill at each sampling location of a DMU was applied to each thicknesses interval of the backfill (e.g. 1 foot, 2 foot, 3 foot, 4 foot) across that entire DMU when characterizing the backfill properties. Because the TOC content is being applied as constant within each DMU: it may over or underestimate the actual TOC content throughout the site given the high variability in TOC content measured in the backfill at the seven sampling locations in February 2016.

For the focused sensitivity analysis evaluating backfill thickness at assumed thicknesses of approximately 1, 2, 3 and 4 ft (30, 60, 90, and 120 cm), TOC content for the backfill material was derived from the specific sampling location. This could either under or overestimate TOC content given the variability seen in the sample locations. Further, PCB sediment concentrations are applied from the seven sampling locations when analyzing the variable backfill thickness. These concentrations were applied in conjunction with the varying backfill thicknesses since each sampling locations is intended to represent an entire DMU. For DMUs with more than one sampling location, samples from both locations were analyzed in order to provide a more thorough evaluation. Again, this may either over or underestimate contaminant migration through the backfill material.

The decision to present PCB concentrations at 50 and 100 years post construction in Tables 1 and 2 is based off guidance and standard practice for sub aqueous capping analyses. Per US Army Corps of Engineers Guidance for In-Situ Subaqueous Capping of Contaminated Sediments, "The design life of most civil works projects such as bridges or dams is 50 years. In contrast, an in-situ cap is conceptually built to last forever" (USACE, 1998). Rather than presenting steady state concentrations of total PCBs, non-steady state results are provided at 50 and 100 years post construction to provide a more realistic estimate for long term conditions at the site.

Several assumptions appear to have minor to no effect on the overall results of the modeling analysis. From the sensitivity analysis, assumptions of no cap decay over time, no decay in bioturbation layer of the cap over time, no deposition on cap, and no cap consolidation after placement all had nominal influence on the overall results. Other parameter assumptions, such as the Darcy Velocity and porosity of the backfill material have significant influence on the results of the model that could result in either an underestimation or overestimation of PCB concentrations. Sensitivity analyses of each of these parameters were performed individually, while holding all other parameters constant. Under conditions where multiple parameters are tested for sensitivity, under- or over- estimation of predicted PCB concentrations is compounded.

Lastly, the model is only capable of predicting potential contaminant migration for PCBs, and is not applicable to other contaminants, specifically metals, that are at the site. Given that metals are highly dependent upon physical parameters at the site, such as salinity, pH, and reduction-oxidation conditions, it is not possible to derive any conclusion from this modeling effort for application to potential metals migration at the site.

Discussion and Recommendations

While there are a number of assumptions and limitations associated with the modeling effort that could result in either an over or under prediction of PCB concentrations and migrations, the primary constraining factor is having only the seven sampling points within the RAB. The granularity of the backfill material in the seven sample locations may not be representative of the entire site, and differences in granularity could impact how the backfill material is predicted to function over time. Also, the inherent heterogeneity of sediment creates some degree of uncertainty as to whether seven samples adequately characterize the PCBs in the RAB for the purposes of this model. Areas with more or less backfill could significantly alter the isolation capabilities of the backfill.

To address these limitations, conservative assumptions were applied in the analysis. The sample with the highest concentration of PCBs within each DMU was chosen to represent the dredge surface for that entire DMU. The model also used varying depths of backfill: the backfill depth as reported by EMJ for each given sample location; as well four different increments of approximately 1, 2, 3, and 4 ft (30, 60, 90, and 120 cm). For those sample locations where the RvAL was not achieved in the average top 45cm in the focused sensitivity analysis of approximately 1, 2, 3, and 4ft (30, 60, 90, and 120cm), greater hypothetical thickness were evaluated to determine how much backfill would be required in order to meet the RvAL. While applying these conservative assumptions allows for an estimated risk of breakthrough for the existing conditions; **USACE recommends that additional evaluation of the as-built conditions be done on the thickness of the backfill throughout the RAB for the purposes of designing any engineering mechanisms to address the breakthrough risk estimates associated with this effort.**

The breakthrough analysis shows that while the existing backfill material overlying the seven sampling locations is generally likely to prevent breakthrough of the PCB contaminated sediments documented in the post-dredge surface (Z-layer) in portions of the site, there are areas where breakthrough may occur. Specifically, backfill in the area of PDS-1 (representative of DMU 5) shows contamination breakthrough in both the 50 and 100 year post construction timeframes. A backfill thickness as great as 360cm may be needed to ensure compliance with the site RvAL in the top 45cm. Low level breakthrough, with concentrations at or slightly above and below the RvAL, is identified at PDS-2, PDS-3, and PDS-7 under the 100 year period of analysis and assuming the measure backfill thickness recorded at those location. Under the scenarios of variable backfill thickness ranging from approximately 1 to 4 ft (30 to 120 cm), breakthrough is seen in almost all backfill thicknesses when applied to the z-layer PCB sediment concentration measured at each sampling location. Sample locations PDS 2, 3, and 5 would require a hypothetical backfill thickness of 150, 150, and 210cm, respectively, in order to ensure compliance with the site RvAL in the top 45cm The only locations with relatively less or no breakthrough are PDS-4 (representing DMU 2) and PDS-6 (representing DMU 1).

USACE provided a qualitative analysis and documented additional concerns regarding the nature of the backfill material in March of 2016 (attached) prior to the modeling effort, which should still be given consideration. **Specifically: the physical nature of the backfill material is not typical for cap design and construction.** The nature of the backfill material is considered a coarse aggregate (15-60% passing 3/8" square). Due to the coarse nature of the backfill material, there is likely to be large interstitial spacing, minimal cohesiveness, and low organic carbon content. While the model does account for the granularity and porosity of the material, site specific porosity at the Jorgensen Forge Early Action Area is unknown and porosity values were derived from site specific data at Terminal 117 and Slip 4. This likely results in an overestimation of the backfill at the site to provide adequate isolation. **Guidance for In-Situ Subaqueous Capping of Contaminated Sediments (EPA, 1998) recommends that a more finely grained (>1/8mm) material be considered for cap design and construction, as opposed to the granular sand (>2mm) or coarse sand (>1/2mm) used at the site, in order to provide a proper isolation barrier and inhibit flux into and through the cap.**

Based on the results of this modeling effort, USACE recommends additional work be performed to first accurately characterize the exact backfill thickness throughout the site based on a comparison of bathymetric surveys conducted prior to and immediately after backfill placement . **Generally, areas with less than 5 ft of backfill are likely to experience the greatest degree of contaminant breakthrough that could lead to unacceptable levels of risk.** DMU 5 and the coffer dam, represented by PDS 1 and 7, would experience greater breakthrough unless they backfill thickness was greater than 330 and 360cm, respectively. USACE believes the current material used at the site is not conducive to providing overall isolation of PCBs throughout the entire site. A more granular backfill in the form of sand (rather than cobble), along with a uniformly higher TOC content, would ensure long term isolation of PCBs at depth throughout the entire site. Addition of amendments, such as activated carbon or organoclay, should also be considered for application to throughout the entire site.

Attachments

Attachment 1. March 2016 Memorandum

Appendix A: QAPP

Jorgensen Preliminary Qualitative Sediment Remedy Analysis
March 2016

A preliminary assessment of the site conditions at EMJ was conducted by qualitatively evaluating the nature of the backfill material and contaminant concentration at the site. USACE's Guidance for In-Situ Subaqueous Capping of Contaminated Sediments (1998) was referenced to assess if the physical nature of the backfill would sufficiently function as a cap due to the remaining contamination at depth and given the existing conceptual site model.

A few qualitative observations were made which suggest a more robust, quantitative analysis should performed to determine cap sufficiency:

1) The backfill is covering native sediments ranging in concentration of 23 mg/kg OC to 167 mg/kg OC total PCBs. This concentration range is greatly elevated relative to the Lower Duwamish Waterway Superfund Remedial Action Level of 12 mg/kg OC for total PCBs.

2) The physical nature of the backfill material is not typical for cap design and construction. The nature of the backfill material is considered a coarse aggregate (15-60% passing 3/8" square). Due to the coarse nature of the backfill material, there is likely to be large interstitial spacing, minimal cohesiveness, and low organic carbon content. Capping guidance recommends that a more granular material be considered for cap design and construction in order to provide a proper isolation barrier and inhibit flux into and through the cap.

3) Backfill thickness is unknown/uncertain throughout the site. Given that a primary function of the cap is to provide physical isolation, thickness must be sufficient to protect the burrowing benthic environment. Bioturbation has been witnessed to depths of 16cm (~0.5ft) in the LDW. If Backfill thickness is less than 1ft (32cm) in areas, it should be assumed that the backfill does not provide proper physical isolation to protect benthic environment.

4) Slope stability considerations along the perimeter of the site have not been fully evaluated. Evidence has emerged in the most recent sampling event that some quantity of backfill in these perimeter areas has potentially slid downgradient into the navigation channel due to high slopes. Should the integrity of the backfill be compromised along the perimeter of the site, functionality of the material as a cap would be compromised.

5) The original placement methods for the backfill need to be evaluated in detail to determine if proper methodology was implemented to reduce resuspension of contaminants during placement. Resuspension of contaminated sediments would likely result in contamination through the cap material and reduce functionality of the backfill to provide a proper isolation barrier.

6) While erosion potential is likely to be decreased due to the nature of the coarse aggregate at the site, a more quantitative analysis should be conducted to determine if any portion of the backfill is subject to strong erosive forces such as tug scour that would warrant additional armoring to ensure the existing backfill thickness is maintained.

7) Advection of contaminants due to an upward hydraulic gradient needs to be given further consideration and taken into account when determining cap design. If groundwater upwelling is present at the site, additional design considerations should be evaluated to ensure functionality.

QUALITY ASSURANCE PROJECT PLAN

Breakthrough Analysis of the Removal Action Boundary Backfill

Jorgen Forge Early Action Area Removal Action

Prepared for

The United State Environmental Protection Agency, Region 10

By the

Seattle District, U.S. Army Corps of Engineers

August 15, 2016

Approval Page

Rebecca Chu

EPA Region 10 Remedial Project Manager: Becky Chu

10/4/16

Date

EPA Region 10 Quality Assurance Manager: Donald Brown

10/4/16

Date

USACE Technical Team Lead: Kristen Kerns

10/5/2016

Date

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Appendix A 9

1. Project Organization

This Quality Assurance Project Plan (QAPP) includes information concerning the modeling effort conducted by the US Army Corps of Engineers (USACE) Seattle District at the request of the US Environmental Protection Agency (EPA) Region 10 to evaluate isolation properties of backfill placed in the Remedial Action Boundary (RAB) at the Jorgensen Forge Early Action Area. This QAPP meets the requirements of the Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA (EPA, 1988). All QA/QC procedures and project content detailed in this QAPP are in accordance with EPA Guidance for Quality Assurance Project Plans (G-5) and Data Quality Objectives Systematic Planning (G-4).

Table 1. Project Team

Team Member, Organization	Title	Contact Information	Role/Responsibility
Becky Chu, USEPA Region 10	Remedial Project Manager	Chu.Rebecca@epa.gov Phone: 206-553-1774	Superfund Site Remedial Project Manager. Will provide direction on applicability to site-related decisions.
Donald Brown, USEPA Region 10	QA Manager	brown.donaldm@epa.gov Phone: 206-553-0717	Quality Assurance Approval
Kristen Kerns, USACE Seattle District	Senior Technical Lead	kristen.kerns@usace.army.mil Phone: 206-764-3474	Primary technical lead responsible for overall execution of the technical components of the modeling effort.
David Clark, USACE Seattle District	Technical Support	David.s.clark@usace.army.mil	Provides support related to technical components of the modeling effort.

2. Project Background and Problem Definition

Background

In accordance with the EPA-approved Removal Action Work Plan (dated June 2014) prepared by Anchor QEA, backfill material was placed throughout the in-water dredging area (also referred to as the RAB) to restore the post-construction elevations to the pre-dredging elevations (Anchor QEA 2014) following contaminated sediment removal in September 2014. Analytical results for the Z-layer samples of the dredge prism were not available until after completion of the backfill placement. The analytical results of the Z-layer samples showed that the sediment Removal Action Level (RvAL) of 12 mg/kg OC (130 ug/kg dw) for total PCBs (as Aroclors) was not achieved in all 7 in-waterway locations sampled for compliance.

Problem Definition

EPA's Action Memorandum (2011) required a complete removal of all contaminated sediments above the RvALs for the Contaminants of Concern (COCs). Because the sediment RvAL of 12 mg/kg OC (130 ug/kg dw) for total PCBs (as Aroclors) was not achieved in all Z-layer samples analyzed for compliance, EPA is now evaluating the backfill material placed within the RAB for its ability to function as an isolation barrier for the contamination remaining at depth. Because the original intent of the backfill placement was simply to restore the site to pre-dredging elevations, the backfill was not designed or placed with the intent of serving as an isolation barrier.

As such, an analysis of the backfill will be conducted to evaluate whether the placed backfill material will provide adequate isolation to meet the Removal Action Level for the site, which is 12 mg/kg OC (130 μg/kg dw) for PCBs. The analysis of the backfill was also conducted to evaluate both the top 45 cm of material, in addition to the top 10 cm. The additional interval of the top 45 cm was added based on early discussions with EMJ regarding points of compliance associated with a capping alternative, pre finaliziation of the EE/CA (2008 letter from Shawn Blocker to Peter Jewitt). Compliance with these RvALs will be evaluated through application of steady state and transient cap performance models designed to evaluate chemical breakthrough at a depth of interest both under steady state conditions and as a function of time.

Note that the RvAL for this site is the same value as the Remedial Action Level (RAL) established by the Lower Duwamish Waterway (LDW) Record of Decision (EPA, 2014). Similarly, the ROD specifies that for Recovery Category 1, the top 45 cm is the target interval for sediment depth. Therefore, in addition to the analysis being consistent with the EMJ Removal Action, it is also consistent with the LDW ROD requirements.

Total PCBs do exist in a dissolved phase in sediment. While it is true that PCBs are very hydrophobic and absorb to carbon in sediment, there is typically a significant bioavailable fraction that is still present in porewater. This is mathematically illustrated through the calculation: Cpw = Csed/(Foc*Koc). This porewater fraction of PCBs will migrate upward over time, either through flux processes or from groundwater upwelling, which is likely given the proximity of the site to the upland and hydraulic gradient to the river. These transport processes can play an important role in moving dissolved phase PCBs in porewater up through backfill or cap material. As the porewater migrates upward through the backfill, it will incur some residence time with the recently added carbon that has been placed at the site in the backfill material. This carbon, in the form of TOC, will absorb some of the dissolved phase PCBs in the porewater during the process of upward migration. The more TOC present in the backfill, the more absorption will occur. Thus, parameters such as TOC in backfill, as well as the TOC in the native sediment, along with diffusion and dispersion play an important role in determining potential for contaminant breakthrough over time.

To summarize: the results of this modeling effort can be used to interpret whether the placed backfill material at the Jorgensen Forge Early Action Area will provide sufficient chemical isolation to adequately protect human health and the environment, per the goals of the Removal Action. Because of the overlap with the goals with the LDW ROD, it will also be consistent with the LDW Record of Decision's RAL of 12 mg/kg OC (130 ug/kg dw).

3. Task Description

Scope

The primary scope of this effort consists of identifying and compiling parameters for input to the 2 layer sediment cap model and providing a summary of model outputs. The Excel spreadsheet model (provided in Appendix A) contains three worksheets:

1) A two layer (bioturbation and chemical isolation layer) analytical model of steady state cap performance
2) A one layer (chemical isolation layer) analytical model of transient cap performance
3) A sensitivity analysis of the two layer steady state model

A complete description of these models is provided in the user's manual in Appendix A. 27 different input parameters are required for both the two layer and one layer models. The source of these input parameters are primarily from previous studies associated with the LDW, literature derived, or default model parameter values. Of the 27 different input parameters, 5 will vary with the 7 sample locations taken within the RAB. Data associated with these 7 sample locations were collected in 2014 and 2016, with split samples analyzed by EPA in 2016. Sample data for both years as well as the splits will be run through the model. A sensitivity analysis will also be utilized for a subset of parameters.

Once the model has been set up and run for all sample locations, a summary report of findings will be developed and provided to EPA for review and comment.

Schedule

Table 2. Schedule

Task	Approximate Duration (working days)
Notice to Proceed from EPA RPM	0 days
Identify model inputs and run model	20 days
Draft summary report	5 days
EPA review/comment on summary report	5 days
Revise and finalize summary report	5 days

4. Data Quality Objectives and Criteria

Data Quality Objectives (DQOs) are qualitative and quantitative statements that clarify the intended use of data, define the types of data needed to support a decision, identify the conditions under which the data should be collected, and specify tolerable limits on the probability of making a decision error because of uncertainty in the data. Data of known and documented quality are essential to the success of any modeling study which will be used to generate information for use in decision making. All data used in this modeling effort will be reviewed for quality and consistency with other relevant data and for reasonableness in representing known conditions of the study area.

The objective of this modeling effort is to evaluate if the placed backfill material will provide adequate isolation over time to meet the RvALs established by the EMJ Action Memorandum (2011) within the biologically active zone. Given that the original design of the backfill for the RAB was not previously designed to function with the intent of serving as an isolation barrier, an analysis must be done through this modeling effort to determine if the current conditions at the site are conducive to providing adequate isolation such that RvALs for the LDW can be maintained over time. This modeling effort will evaluate existing conditions derived from site specific data for the Jorgensen Forge Early Action Area collected in 2014 and 2016. Some parameters are substituted with default parameters or data collected for the LDW Remedial Investigation/Feasibility Study. The traditional application and best use of the model utilized in this analysis is for preliminary design of a cap. However, this model can also be applied to also analyze existing conditions of a site. As such, the model is intentionally run with conservative parameters to ensure the evaluation of the existing backfill material at the site will provide proper isolation of contamination at depth. This requires selection of conservative values for multiple parameters in order to address any potential uncertainty in the existing data.

This modeling effort will be achieved through use of the 2 Layer Analytical Model, Version 1.18 developed by Lampert and Reible (Appendix A). This model has been used for various capping analyses and most recently used at the Terminal 117 Early Action Area in the LDW to evaluate backfill effectiveness as an isolation layer. This model was selected for use at the Jorgensen Forge Early Action Area because it can provide a reliably accurate representation of the current site and sediment conditions using parameters collected from the Jorgensen Forge Early Action Area or other comparable LDW sources. Where there are no available site specific data for the RAB, alternate sources for the model input parameters will be largely based on other Superfund studies conducted in the LDW, including Terminal 117 and Slip 4. Given that these data are representative of conditions within the LDW and were collected under the regulatory authority of the Superfund program to meet a similar data use, these data meet the quality criteria necessary for this study.

Modeling scenarios will be run for the seven different sampling locations within the RAB at the Jorgensen Forge Early Action Area. Data is available for two different years, 2014 and 2016, at these sample locations. Modeling analysis will be conducted for both the 2014 and 2016 data sets. For some parameters, specifically % TOC in the backfill material, data was only collected in 2016. As such, this data point from 2016 will be used in model runs for both the both 2014 and 2016 data. Split samples for PCB analysis were collected and analyzed by EPA during the 2016 sampling event; data from these sample locations will also be run through the model as necessary.

A second objective of this effort will be to conduct a focused sensitivity analysis of the backfill thickness, given the known variability of the backfill throughout the site. Based on a visual review of post dredge and backfill surveys presented in the Pre-Final Certification Inspection Letter Report (2016), there are areas within the RAB with less than 2ft of backfill present. Given this, a sensitivity analysis to illustrate the potential for breakthrough will be conducted assuming 1, 2, and 3 feet of backfill thickness.

Input parameters for the model along with the originating data source for each input is provided in Table 3.

Table 3. Model Input Parameters

Parameter	Value	Units	Notes	Source
Contaminant Properties				
Contaminant	PCBs			
Octanol-water partition coefficient, log K_{ow}	6.8		Value for Aroclor 1260 as surrogate for all PCBs; LDW FS states that 1260 is a common PCB in the LDW	US Dept. of Health and Human Services (1993). Toxicology Profile for Selected PCBs (Aroclor -1260, 1254, -1248, -1242, -1232, -1221, and -1016), ATSDR-TP- 92/16, p. 113
Water Diffusivity, D_w	5.0E-06	cm^2/s	Mid value, also measured value from Slip 4	AECOM (2012). LDW Final Feasibility Study, Appendix C
Cap Decay Rate, l_1	0	yr^{-1}	Assume no decay; Default model value	Lampert and Reible (2009). An Analytical Modeling Approach for Evaluation of Capping of Contaminated Sediments," Soil & Sediment Contamination, 2009, 18(4):470-488
Bioturbation Layer Decay Rate, l_2	0	yr^{-1}	Assume no decay; Default model value	Lampert and Reible (2009)
Sediment Properties				
Contaminant Pore Water Concentration, C_0	varies	ug/L	Calculated as contaminant concentration dw/(F_{oc}*K_{oc}), where F_{oc} is a measured value at each individual sample location	Anchor QEA (2014 and 2016). Sediment Z-Layer Results; EPA (2016) Split Sample Results
Biological Active Zone of Zlayer, fraction organic carbon, $(f_{oc})_{bio}$	0.0005	N/A	Measured value at each individual sample location	Anchor QEA (2014 and 2016). Sediment Z-Layer Results
Colloidal Organic Carbon Concentration, r_{DOC}	2	mg/L	Mid value	AECOM (2012). LDW Final Feasibility Study, Appendix C
Darcy Velocity, V (positive is upwelling)	250	cm/yr	Estimate; based on T-117; no site specific EMJ data available	Crete (2014). Capping Model Evaluation of Maximum Protective Total PCB Concentrations in DU-1
Depositional Velocity, V_{dep} *(positive is deposition of sediments)*	0	cm/yr	Assume no deposition to account for variation in sedimentation (ie erosional or depositional)	AECOM (2012). LDW Final Feasibility Study
Bioturbation Layer Thickness, h_{bio}	45	cm	LDW ROD point of compliance	EPA (2014). LDW Record of Decision
Pore Water Biodiffusion Coefficient, D_{bio}^{pw}	100	cm^2/yr	Default model value	Lampert and Reible (2009)
Particle Biodiffusion Coefficient, D_{bio}^{p}	1	cm^2/yr	Default model value	Lampert and Reible (2009)
Cap Properties				
Conventional Cap placed depth	varies	cm	Cap thickness does not include transition zone between backfill and native	EMJ CQAP Data Report, Appendix C "Field Logs, Sonic Processing Logs"
Cap Materials -Granular (G) or Consolidated Silty/Clay (C)	G		Based on backfill specs and confirmed w/ field observations during sampling	CalPortland (2103). Cal Portland Aggregate Submittal, June 14, 2013
Cap consolidation depth	0	cm	Slip 4 estimate	AECOM (2012). LDW Final Feasibility Study, Appendix C
Underlying sediment consolidation due to cap placement	11.5	cm	Assume midpoint btw Slip 4 estimate (23cm) and T117 estimate (0cm)	AECOM (2012). LDW Final Feasibility Study, Appendix C; Crete (2014). Capping Model Evaluation of Maximum Protective Total PCB Concentrations in DU-1
Porosity, e	0.4		Slip 4, T117 estimate	AECOM (2012). LDW Final Feasibility Study, Appendix C; Crete (2014). Capping Model Evaluation of Maximum Protective Total PCB Concentrations in DU-1
Particle Density, ρ_P	2.65	g/cm^3	Assume midpoint btw Slip 4 estimate (2.6) and T117 estimate (2.7)	AECOM (2012). LDW Final Feasibility Study, Appendix C; Crete (2014). Capping Model Evaluation of Maximum Protective Total PCB Concentrations in DU-1
fraction organic carbon, $(f_{oc})_{eff}$	varies		Measured value at each individual sample location	Anchor QEA (2014 and 2016). Sediment Z-Layer Results
Depth of Interest, z	45	cm	Same as bioturbation layer thickness	EPA (2014). LDW Record of Decision
Fraction organic carbon at depth of interest, $f_{oc}(z)$	varies		Same as BAZ F_{oc}	Anchor QEA (2014 and 2016). Sediment Z-Layer Results
Commonly Used Parameter Estimates				
Organic Carbon Partition Coefficient, log K_{oc}	5.54	log L/kg	Calculated as log(350000), where 3.5x10^5 = K_{oc} for Aroclor 1260; RSL Table	EPA (2016). May 2016 RSL Table
Colloidal Organic Carbon Partition Coefficient, log K_{DOC}	5.17	log L/kg	Default model value	Lampert and Reible (2009)
Boundary Layer Mass Transfer Coefficient, k_{bl}	0.75	cm/hr	Default model value	Lampert and Reible (2009)
Dispersivity, α	12.80	cm/hr	Default model value	Lampert and Reible (2009)
Effective Cap Layer Diffusion/Dispersion Coeff., D_1	3247	cm^2/yr	Default model value	Lampert and Reible (2009)
Bioturbation Layer Diffusion/Dispersion Coeff., D_2	7899	cm^2/yr	Default model value	Lampert and Reible (2009)

5. Specialized Training

Kristen Kerns is the senior technical lead for this effort. Kristen holds a BS in Environmental Science and a MS in Environmental Health. Kristen has worked for the Army Corps of Engineers for 8 years. During this time, she has served as the technical lead for a number of sediment remediation projects, including several in the Lower Duwamish Waterway. She has experience designing and evaluating different types of isolation caps for sediments, including application and evaluation of modeling results similar to the models used in this effort for the Jorgensen Forge Early Action Area.

David Clark is providing technical support for this effort. David holds a BS in Political Science and a MS in Marine Affairs. David has worked for the Army Corps of Engineers for 4 years. He is the technical lead for the overall Jorgensen Forge Early Action Area. David has historical knowledge of the Jorgensen Forge Early Action Area, providing construction oversight and technical support to the EPA for the removal action.

6. Documentation and Records

The final approved QAPP, technical memorandum summarizing model results, and all model outputs will be provided to the EPA RPM.

The model is based in Microsoft Excel. The model and all model inputs/outputs will be stored on the USACE Seattle District's local server.

7. Data Review, Verification and Validation

The two layer steady state and one layer transient cap performance models have previously undergone calibration and validation and thus will not be recalibrated or validated specifically for this effort.

All model inputs will be reviewed for quality and consistency with other relevant data and for reasonableness in representing known conditions of the study area. This review will also provide cross checks on data handling to ensure no transcription errors.

The source of all data used for model input is previously published information, primarily from the Lower Duwamish Waterway Superfund Project, Jorgensen Forge Early Action Area, Slip 4, and Terminal 117 early Action Area. This source data for input into the model has all undergone various stages of data validation, per the requirements of each individual project and in accordance with Superfund requirements.

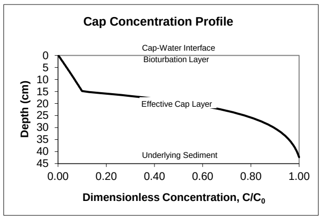
All model outputs will include a printout of input parameters as well as associated outputs.

Appendix A

Excel Spreadsheet Models and Users Guide

STEADY-STATE CAP DESIGN MODEL
from Lampert and Reible (2009)*
Version 1.19
6/8/2012

Instructions: This spreadsheet determines concentrations and fluxes in a sediment cap at steady-state, assuming advection, diffusion, dispersion, bioturbation, deposition/erosion, sorption onto colloidal organic matter, and boundary layer mass transfer. The deposition velocity is negative in the case of erosion, and is assumed to be constant and to have minimal effect on the thickness of the cap. The cells in GREEN are input cells; these can be changed for the design of interest. Cells in YELLOW are commonly used parameter estimates. These can be changed but note that physically unrealistic parameter values may result. A second worksheet calculates the transient profiles for a semi-infinite case. DO NOT CHANGE THE CELLS IN RED (or the spreadsheet will not function properly). These are calculated values for model outputs. The third worksheet title "array" allows the user to create an array of outputs for a given input (e.g., to study different compounds for a given site).



z/hcap		
0	0.01	1
0.00	0.42	42.31
0.00	0.00	1.00
0.00	0.00	1.00

Contaminant Properties

Contaminant	PHE	
Octanol-water partition coefficient, log K_{ow}	4.57	
Water Diffusivity, D_w	6.0E-06	cm^2/s
Cap Decay Rate, λ_1	0.00	yr^{-1}
Bioturbation Layer Decay Rate, λ_2	0.00	yr^{-1}

Sediment Properties

Contaminant Pore Water Concentration, C_0	1	ug/L
Biological Active Zone fraction organic carbon, $(f_{oc})_{bio}$	0.05	
Colloidal Organic Carbon Concentration, ρ_{DOC}	0	mg/L
Darcy Velocity, *V* (positive is upwelling)	10	cm/yr
Depositional Velocity, V_{dep} *(positive is deposition of sediments)*	0	cm/yr
Bioturbation Layer Thickness, h_{bio}	15	cm
Pore Water Biodiffusion Coefficient, D_{bio}^{pw}	100	cm^2/yr
Particle Biodiffusion Coefficient, D_{bio}^{p}	1	cm^2/yr

Cap Properties

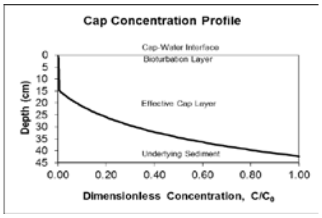
Conventional Cap placed depth	45	cm
Cap Materials -Granular (G) or Consolidated Silty/Clay (C)	G	
Cap consolidation depth	0	cm
Underlying sediment consolidation due to cap placement	15	cm
Porosity, ε	0.4	
Particle Density, ρ_P	2.6	g/cm^3
fraction organic carbon, $(f_{oc})_{eff}$	0.0002	
Depth of Interest, *z*	15	cm
Fraction organic carbon at depth of interest, $f_{oc}(z)$	0.05	

Commonly Used Parameter Estimates

Organic Carbon Partition Coefficient, log K_{oc}	4.22	log L/kg	
Colloidal Organic Carbon Partition Coefficient, log K_{DOC}	3.85	log L/kg	
Boundary Layer Mass Transfer Coefficient, k_{bl}	0.75	cm/hr	
Dispersivity, α	2.12	cm	(not allowed to be less than 1 cm)
Effective Cap Layer Diffusion/Dispersion Coeff., D_1	77	cm^2/yr	
Bioturbation Layer Diffusion/Dispersion Coeff., D_2	1474	cm^2/yr	

Output

Pore Water Concentration at Depth, *C(z)*	0.101	ug/L
Loading at Depth, *W(z)*	83.8	ug/kg
Average Bioturbation Layer Loading, $(W_{bio})_{avg}$	43	ug/kg
Flux to Overlying Water Column, *J*	103	$ug/m^2/yr$
Cap-Bioturbation Interface Concentration, C_{bio}/C_0, C_{bio}	10.08%	
Cap-Water Interface Concentration, C_{bl}/C_0, C_{bl}	0.16%	
Average Bioturbation Concentration, $(C_{bio})_{avg}/C_0$, $(C_{bio})_{avg}$	5.20%	
Characteristic Time to~1% of steady state, $t_{adv/diff}$	2.8	yr



Dimensionless Parameters

Effective Cap Layer Peclet No., Pe_1	3.55
Effective Cap Layer Damkohler No., Da_1	0.00
β = SQRT(Pe_1^2/4+Da_1)	1.78
Bioturbation Layer Peclet No., Pe_2	0.10
Bioturbation Layer Damkohler No., Da_2	0.00
γ = SQRT(Pe_2^2/4+Da_2)	0.051
Sherwood Number at Interface, *Sh*	66.6

Other Parameters

Cap final thickness, h_{cap}	42.31	cm	
Cap Effective thickness w/ot bioturbation layer, h_{eff}	27	cm	
Containment Layer Retardation Factor, R_1	6		
Bioturbation Layer Retardation Factor, R_2	1297		
Effective Advective Velocity, *U*	10.00	cm/yr	(not allowed to be more negative than that which will offset diffusion)
Characteristic Advection Time-cap layer, t_{adv}	15.3	yr	
Characteristic Diffusion Time-cap layer, t_{diff}	3.4	yr	
Characteristic Reaction Time-cap layer, t_{decay}	infinity	yr	

*Lampert, D.J. and Reible, D.D. 2009. "An Analytical Modeling Approach for Evaluation of Capping of Contaminated Sediments," Soil & Sediment Contamination, 2009, 18(4):470-488.

TRANSIENT MODEL
from Van Genchten 1981*
Instructions: The values in the "Parameter" Cells are linked to those on the "Steady State Conditions" page. DO NOT CHANGE THE CELLS IN RED; feel free to change the cells with GREEN color to create an array of concentration profiles.

Model Equations:

$$\xi = \frac{h_{cap} - z}{h_{cap}} \qquad \tau = \frac{D_1 t}{h_{cap}^2 R_1} \qquad Pe = \frac{U h_{cap}}{D_1} \qquad u = \sqrt{\frac{Pe^2}{4} + \frac{\varepsilon \lambda h_{cap}^2}{D_1}}$$

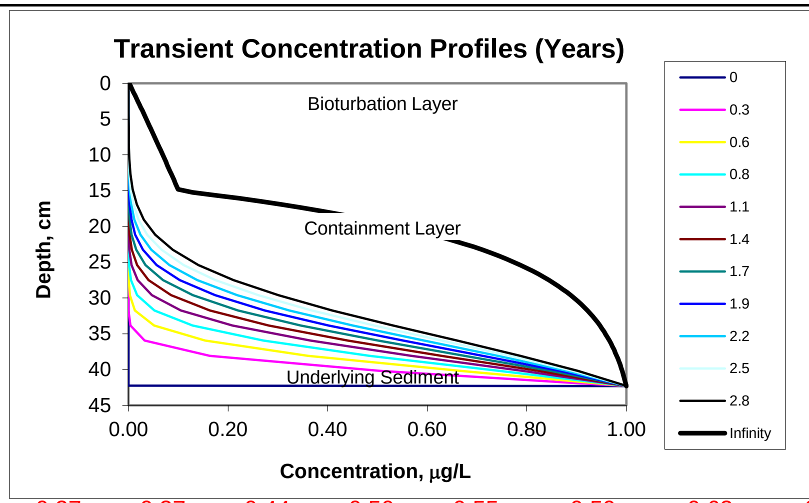
$$C/C_0 = 0.5\left\{\begin{array}{l}\exp\left[\left(\frac{Pe}{2} - u\right)\xi\right]\mathrm{erfc}\left[\frac{1}{2\tau^{0.5}}(\xi - 2u\tau)\right] + \\ \exp\left[\left(\frac{Pe}{2} + u\right)\xi\right]\mathrm{erfc}\left[\frac{1}{2\tau^{0.5}}(\xi + 2u\tau)\right]\end{array}\right\}$$

Parameters

$t_{avd/diff}$	2.8 yr	2.77142	ss time
Pe	5.5		
Da	0.0		
u	3		

Dimensionless Calculations

zeta	tau: 0	0.002	0.004	0.006	0.009	0.011	0.013	0.015	0.017	0.019	0.021
1	0.00	0.00	0.00								.00
0.95	0.00	0.00	0.00								.00
0.9	0.00	0.00	0.00								.00
0.85	0.00	0.00	0.00								.00
0.8	0.00	0.00	0.00								.00
0.75	0.00	0.00	0.00								.00
0.7	0.00	0.00	0.00								.00
0.65	0.00	0.00	0.00								.01
0.6	0.00	0.00	0.00								.02
0.55	0.00	0.00	0.00								.03
0.5	0.00	0.00	0.00								.05
0.45	0.00	0.00	0.00								.09
0.4	0.00	0.00	0.00								.14
0.35	0.00	0.00	0.00								.21
0.3	0.00	0.00	0.00								.30
0.25	0.00	0.00	0.01								.41
0.2	0.00	0.00	0.05								.53
0.15	0.00	0.03	0.15	0.27	0.37	0.44	0.50	0.55	0.59	0.63	0.66
0.1	0.00	0.16	0.36	0.48	0.57	0.63	0.68	0.71	0.74	0.77	0.79
0.05	0.00	0.51	0.67	0.74	0.79	0.82	0.85	0.87	0.88	0.89	0.90
0.01	0.00	0.90	0.94	0.95	0.96	0.97	0.97	0.98	0.98	0.98	0.98
0.001	0.00	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00



Concentration Profiles

depth	time: 0.0	0.3	0.6	0.8	1.1	1.4	1.7	1.9	2.2	2.5	2.8
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.11574498	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.23148995	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.34723493	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8.4629799	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.5787249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12.6944699	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.8102148	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
16.9259598	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02
19.0417048	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03
21.1574498	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.04	0.05
23.2731947	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.05	0.07	0.09
25.3889397	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.06	0.08	0.11	0.14
27.5046847	0.00	0.00	0.00	0.00	0.02	0.04	0.07	0.10	0.14	0.17	0.21
29.6204297	0.00	0.00	0.00	0.02	0.05	0.09	0.13	0.17	0.22	0.26	0.30

31.7361746	0.00	0.00	0.01	0.05	0.11	0.16	0.22	0.27	0.32	0.37	0.41
33.8519196	0.00	0.00	0.05	0.13	0.21	0.28	0.35	0.40	0.45	0.49	0.53
35.9676646	0.00	0.03	0.15	0.27	0.37	0.44	0.50	0.55	0.59	0.63	0.66
38.0834096	0.00	0.16	0.36	0.48	0.57	0.63	0.68	0.71	0.74	0.77	0.79
40.1991545	0.00	0.51	0.67	0.74	0.79	0.82	0.85	0.87	0.88	0.89	0.90
41.8917505	0.00	0.90	0.94	0.95	0.96	0.97	0.97	0.98	0.98	0.98	0.98
42.2725846	0.00	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
42.3148995	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

*Van Genuchten, M.T. 1981. “Analytical solutions for chemical transport with simultaneous adsorption, zero order production and first order decay.” Journal of Hydrology, 49(3):213-233.

STEADY-STATE CAP DESIGN MODEL -- Array/Multiple Contaminant Worksheet

Instructions: Copy column "C" to create multiple solution rows; then change the parameters/chemical of interest.
Column "B" is linked to the front worksheet. This example shows the effect of log Kow.

Inputs

Contaminant	PHE	PHE	PHE	PHE	PHE	PHE	PHE	PHE	PHE	PHE	PHE	PHE	PHE	PHE	PHE	
Octanol-water partition coefficient, log K_{ow}	4.57	4.58	4.59	4.6	4.61	4.62	4.63	4.64	4.65	4.66	4.67	4.68	4.69	4.7	4.71	
Water Diffusivity, D_w	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	0.000006	cm^2/s
Cap Decay Rate, λ_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	yr^{-1}
Bioturbation Layer Decay Rate, λ_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	yr^{-1}
Contaminant Pore Water Concentration, C_0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ug/L
Biological Active Zone fraction organic carbon, $(f_{oc})_{bio}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
Colloidal Organic Carbon Concentration, ρ_{DOC}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	mg/L
Darcy Velocity, V (positive is upwelling)	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	cm/yr
Depositional Velocity, V_{dep}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	cm/yr
Bioturbation Layer Thickness, h_{bio}	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	cm
Pore Water Biodiffusion Coefficient, D_{bio}^{pw}	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	cm^2/yr
Particle Biodiffusion Coefficient, D_{bio}^{p}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	cm^2/yr
Conventional Cap placed depth	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	cm
Cap Materials -Granular (G) or Consolidated (C)	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	
Cap consolidation depth	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	cm
Underlying sediment consolidation	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	cm
Porosity, ε	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
Particle Density, ρ_P	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	g/cm^3
fraction organic carbon, $(f_{oc})_{eff}$	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
Depth of Interest, z	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	cm
Fraction organic carbon at depth of interest, $f_{oc}(z)$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	

Estimates

Organic Carbon Partition Coefficient, log K_{oc}	4.22	4.23	4.24	4.25	4.26	4.27	4.27	4.28	4.29	4.30	4.31	4.32	4.33	4.34	4.35	log L/kg
Colloidal Organic Carbon Partition Coefficient, log K_{DOC}	3.85	3.86	3.87	3.88	3.89	3.90	3.90	3.91	3.92	3.93	3.94	3.95	3.96	3.97	3.98	log L/kg
Boundary Layer Mass Transfer Coefficient, k_{bl}	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	cm/hr
Dispersivity, α	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	cm
Effective Cap Layer Diffusion/Dispersion Coeff., D_1	66	66	66	66	66	66	66	66	66	66	66	66	66	66	66	cm^2/yr
Bioturbation Layer Diffusion/Dispersion Coeff., D_2	1462	1490	1517	1546	1575	1604	1635	1666	1697	1729	1762	1796	1830	1865	1900	cm^2/yr

Outputs

Pore Water Concentration at Depth, $C(z)$	0.457	0.460	0.464	0.468	0.471	0.474	0.478	0.481	0.484	0.488	0.491	0.494	0.497	0.500	0.503	ug/L
Loading at Depth, $W(z)$	379.7	390.7	402.0	413.6	425.4	437.5	449.8	462.5	475.4	488.6	502.1	515.9	530.0	544.5	559.2	ug/kg
Average Bioturbation Layer Loading, $(W_{bio})_{avg}$	43	43	43	43	44	44	44	44	44	44	44	45	45	45	45	ug/kg
Flux to Overlying Water Column, J	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	$ug/m^2/yr$
Cap-Bioturbation Interface Concentration, C_{bio}/C_0	10.03%	9.86%	9.69%	9.52%	9.35%	9.19%	9.03%	8.87%	8.72%	8.56%	8.41%	8.27%	8.12%	7.97%	7.83%	
Cap-Water Interface Concentration, C_{bl}/C_0	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	0.15%	
Average Bioturbation Concentration, $(C_{bio})_{avg}/C_0$, $(C_{bio})_{avg}$	5.18%	5.09%	5.00%	4.91%	4.83%	4.74%	4.66%	4.58%	4.50%	4.42%	4.34%	4.27%	4.19%	4.12%	4.04%	
Characteristic Time to ~1% of pre-cap, $t_{adv/diff}$	3.1	3.2	3.3	3.4	3.4	3.5	3.6	3.7	3.8	3.9	3.9	4.0	4.1	4.2	4.3	yr
Effective Cap Layer Peclet No., Pe_1	4.15	4.16	4.17	4.18	4.18	4.19	4.20	4.21	4.21	4.22	4.23	4.23	4.24	4.24	4.25	
Effective Cap Layer Damkohler No., Da_1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
β = SQRT($Pe_1{}^2$/4+Da)	2.08	2.08	2.08	2.09	2.09	2.10	2.10	2.10	2.11	2.11	2.11	2.12	2.12	2.12	2.13	
Bioturbation Layer Peclet No., Pe_2	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08	
Bioturbation Layer Damkohler No., Da_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
γ = SQRT($Pe_1{}^2$/4+Da)	0.051	0.050	0.050	0.049	0.048	0.047	0.046	0.045	0.044	0.043	0.043	0.042	0.041	0.040	0.040	
Sherwood Number at Interface, Sh	67.1	65.9	64.7	63.5	62.4	61.2	60.1	59.0	57.9	56.8	55.7	54.7	53.7	52.7	51.7	
Cap final thickness, h_{cap}	42.31	42.37	42.42	42.47	42.51	42.56	42.61	42.66	42.70	42.75	42.79	42.83	42.87	42.92	42.96	cm
Cap Effective Depth, h_{eff}	27	27	27	27	28	28	28	28	28	28	28	28	28	28	28	cm
Containment Layer Retardation Factor, R_1	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	
Bioturbation Layer Retardation Factor, R_2	1297	1324	1352	1380	1409	1439	1469	1500	1532	1564	1597	1630	1664	1699	1735	
Effective Advective Velocity, U	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	cm/yr
Characteristic Advection Time-cap layer, t_{adv}	15.3	15.6	15.9	16.3	16.6	17.0	17.3	17.7	18.1	18.5	18.9	19.3	19.7	20.1	20.5	yr
Characteristic Diffusion Time-cap layer, t_{diff}	4.0	4.1	4.1	4.2	4.3	4.4	4.5	4.7	4.8	4.9	5.0	5.1	5.2	5.3	5.5	yr
Characteristic Reaction Time-cap layer, t_{decay}	infinity	infinity	infinity	infinity	infinity	infinity	infinity	infinity	infinity	infinity	infinity	infinity	infinity	infinity	infinity	yr

MODEL OF 2 LAYER SEDIMENT CAP, DESCRIPTION AND PARAMETERS

Version - 2 Layer Analytical Model v.1.18 and Active Cap Layer Model v 4.1

This Excel spreadsheet model contains three worksheets

1. A two layer (bioturbation and chemical isolation layer) analytical model of steady state cap performance
2. A one layer (chemical isolation layer) analytical model of transient cap performance
3. A sensitivity analysis of the two layer steady state model

The steady state analytical model evaluates the long time behavior of a cap, after both the biologically active layer and the underlying cap layer are influenced by contaminant migration from below. It estimates the maximum concentration or flux that can ever be expected from a cap assuming that the underlying concentration is constant. The model implemented in the spreadsheet is a two layer steady state model which predicts concentrations and fluxes in a chemical isolation layer or in the near surface biologically active zone or bioturbation layer. The model is described in detail in Lampert and Reible [1]. The transient model is designed to describe chemical migration in the chemical isolation layer of a cap only. The model is set up to stop calculations at a point in time when the concentration in the bioturbation layer begins to be significant (although the end time of the transient calculation can be overwritten, the user should do so with caution because the transient model does not account for the faster transport and degradation processes in the biologically active zone) . The sensitivity analysis worksheet is designed to allow easy adjustment of model parameters to look at a large number of conditions quickly.

The active cap layer model v 4 is identical to the conventional model (v. 1.18) except that it treats the lower layer as an amended cap layer (e.g. amended with activated carbon or organoclay with assumed linear partitioning) and the upper layer is a conventional sand cap layer. Since both layers are part of the cap, the active cap layer model does not evaluate a bioturbation layer. Previous versions of the active layer model (before v 4) used a different approach to estimate the active layer thickness and the approximations used were valid in only a narrow range of conditions. Because many people were using the model outside of that range of conditions, it was deemed appropriate to eliminate that model and replace it with the v. 4. The modeling remains approximate although the primary limitation of v4 is the use of linear sorption (which is often not a valid assumption for activated carbon, in particular). For

[1] *Lampert, D.J. and Reible, D.D. 2008. "An Analytical Modeling Approach for Evaluation of Capping of Contaminated Sediments," Soil & Sediment Contamination, (under review)."

full simulation of such cases, a numerical model such as CAPSIM 2 should be employed. The latter model is also available from Danny Reible at reible@mail.utexas.edu.

Model parameters and their definitions are shown below. Although the parameters are used to define both the steady state and transient model, note that many are not applicable in the transient model since it describes migration in only a single capping isolation layer (as modified by the effective thickness of an active cap layer). Parameters shown in the spreadsheet in blue are normal model inputs that the user is free to change as needed. Parameters shown in yellow are parameter estimates that employ the user supplied inputs and represent best estimates based upon the author's experience. These parameters can be changed but the reader is cautioned in doing so. Parameters shown in red are integral to the model and these values should not normally be changed.

Values in blue – change as appropriate for your site

Values in yellow – change if you have a more appropriate parameter estimation approach or a measured value

Values in red – should not normally be changed in that they are integral to the model

Contaminant Properties

Contaminant – Identification of contaminant for easy reference

Octanol-water Partition Coefficient, log K_{ow} – Tabulated K_{ow} values are used to estimate contaminant hydrophobicity and to calculate other parameters including organic carbon based partition coefficient and the dissolved organic carbon based partition coefficient.

Water Diffusivity, D_w – diffusivity of the pure contaminant in water, cm^2/sec

Cap Decay Rate (porewater basis), λ_1 – contaminant degradation rate in cap interstitial waters, yr^{-1}

Bioturbation Layer Decay Rate (porewater basis), λ_2 – contaminant degradation rate in interstitial water of surficial biologically active layer in yr^{-1}

Sediment Layer Properties (Active Layer Model- Sediment/Conventional Cap Properties)

Contaminant Pore Water Concentration, C_0 – Interstitial concentration in the near surface layer of the underlying sediment, μg/L

Biological Active Zone fraction organic carbon, $(f_{oc})_{bio}$- (Active Layer model – Conventional cap layer fraction organic carbon) Surficial layer organic carbon content (as a fraction of sediment dry weight), assumed to apply to both the underlying sediment before capping and the surficial cap layer at steady state (after deposition of new sediment).

Colloidal Organic Carbon Concentration, ρ_{DOC} –dissolved organic carbon in sediment and cap interstitial waters, mg/L

Darcy Velocity, V – volume of upwelling water discharging into overlying water body per unit surface area per time, $cm^3/(cm^2 \cdot yr)$. V is forced ≥ 0, that is, losing bodies of water (downward velocity) are estimated conservatively as diffusion only

Depositional Velocity, V_{dep}- rate of deposition of new sediment in cm/yr. The deposition velocity is used to estimate an effective Darcy velocity using the sorption characteristics of the chemical isolation layer. Note that a large deposition velocity can give rise to an ever increasing cap thickness that will give large negative effective velocities. The calculated effective Darcy velocity is limited to that which would offset diffusion to avoid physically unrealistic solutions (i.e. total upward migration cannot be less than 0)

Bioturbation Layer Thickness, h_{bio}- thickness, in cm, of the biologically active layer that will develop at the surface of the cap. Figure 1 shows the probability distribution for this parameter in freshwater (median=4.8 cm) and estuarine systems (median=7.9 cm).

Pore Water Biodiffusion Coefficient, D_{bio}^{pw}- effective diffusion coefficient in biologically active layer based on interstitial water, cm^2/yr. There is very little guidance for this parameter although measurements have shown 10^{-3}-10^{-5} cm^2/s as reasonable estimates. Since the parameter also characterizes organism behavior, using a multiple of the particle diffusion coefficient below (e.g. 100 x D_{bio}^{p}) might be a reasonable estimation method. Note that although the numerical value of this parameter may be larger than D_{bio}^{p}, particle biodiffusion is typically more important due to contaminant sorption on the particles.

Particle Biodiffusion Coefficient, D_{bio}^{p} – effective particle diffusion coefficient in biological active layer, cm^2/yr. Figure 2 shows the probability distribution for this parameter in freshwater (median = 3.3×10^{-8} cm^2/sec=1.06 cm^2/yr) and estuarine systems (median=3×10^{-7} cm^2/sec=9.4 cm^2/yr)

In the active layer model, the preceeding three parameters are replaced with the conventional cap placed thickness, consolidation depth, a calculated conventional cap layer thickness (in red), a cap materials type, a particle density and calculated effective diffusion coefficient (in yellow).

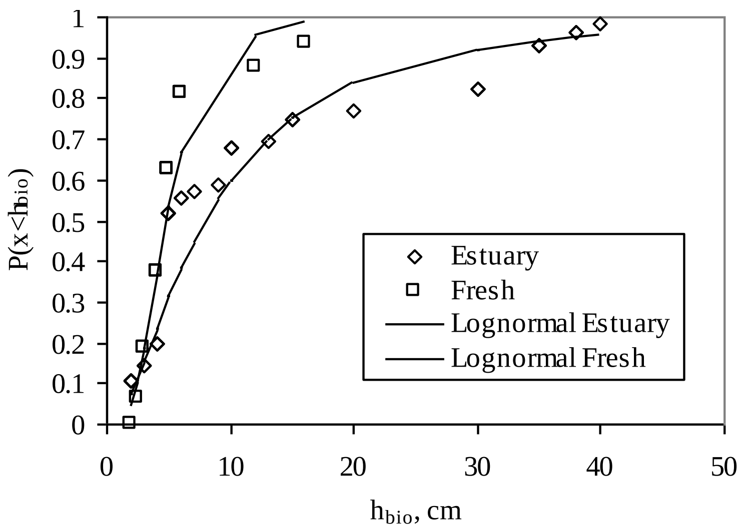


Figure 1- Distribution of measurements of hbio (adapted from Thoms et al., 1995)

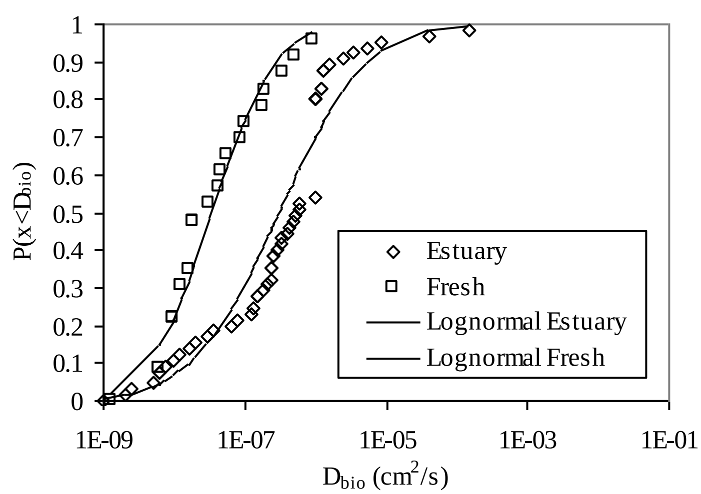


Figure 2 -Distribution of measurements of Dbio (adapted from Thoms et al., 1995)

Cap Properties (Active Cap Properties in the Active Cap model)

Conventional Cap placed depth (total cap placed depth in active layer model)– The depth of placed sand or other conventional cap material, in cm. The effective depth will be less due to bioturbation or consolidation

Cap Materials – If the cap is constructed of sand or similar material, a G (granular) should be entered here, whereas if it is constructed of silt or clay, C should be entered for a consolidated material. Two different models of estimating the effective diffusion coefficient are employed for these two types of materials.

Cap consolidation depth – Depth that the cap consolidates (typically small for a sandy cap), in cm. This does not include the consolidation of the underlying sediment.

Underlying sediment consolidation due to cap placement – Underlying sediment consolidation, in cm. This indicates the total volume of porewater expressed into the cap layer. The migration of a contaminant expressed with this porewater may be considerably less than the total consolidation due to sorption-related retardation in the cap material.

Porosity, ε – Void fraction in conventional cap material

Particle Density, *ρ* - Cap amendment density, in g/cm^3 (note- in the active cap model this does not have to be total density but only the density of the active material in the cap)

Fraction organic carbon, $(f_{oc})_{eff}$ – Fraction organic carbon in conventional cap material

In the active cap layer model, this parameter is replaced with an effective Kd (assumed constant for linear partitioning) in the active layer

Depth of Specific Interest below cap-water interface, *z* – If performance (as indicated by porewater or bulk solid phase concentration) at a particular distance below the cap surface is desired, this depth can be entered here, in cm.

Fraction organic carbon at depth of interest, $f_{oc}(z)$- Fraction organic carbon at the depth of interest which is used to estimate the bulk solid phase concentration from the porewater concentration with the relationship $W=K_{oc}\ f_{oc}\ C_{pw.}$ Use of this parameter allows one to use the fraction organic carbon of either the biologically active zone or the underlying cap layer if the depth of interest is set at the bottom of the biologically active zone.

Steady State Equivalent Cap thickness, h_{cap} – Calculated effective thickness of overall cap for steady state calculations including both sand cap and active cap layer, in cm

Transient Equivalent cap thickness, h_{equiv} - Calculated effective thickness of overall cap for transient calculations including both sand cap and active cap layer, in cm

Effective cap partition coefficient – Calculated effective cap partition coefficient in L/kg

<u>Commonly Used Parameter Estimates (can be changed)</u>

Organic carbon based Partition Coefficient, log K_{oc} – This quantity is calculated from the formula 0.903logKow+0.094 (Baker[2]. The Koc is used to estimate the sediment-water partition coefficient through the formula $K_d=K_{oc}f_{oc}$ where f_{oc} is the fraction organic carbon of the layer of interest. Note that inorganic contaminants can be simulated by including an effective Log K_d as the Log K_{oc} entry and choosing $f_{oc}=1$

Colloidal Organic Carbon Partition Coefficient, log K_{DOC} – dissolved organic matter can increase the mobile fraction of contaminant. For PAHs, Burkard[3] has suggested $\log K_{doc} = \log K_{ow} - 0.58$ where K_{ow} is the tabulated octanol-water partition coefficient

Boundary Layer Mass Transfer Coefficient, k_{bl} – benthic boundary layer mass transfer coefficient, cm/yr . A typical value is 1 cm/hr. A useful model of this parameter is

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[2] Baker, J.R., Mihelcic, J.R., Luehrs, D.C., and Hickey, J.P. 1997. "Evaluation of Estimation Methods for Organic Carbon Normalized Sorption Coefficients," Water Environment Federation, 69(2):136-145.

[3] Burkhard LP. 2000. Estimating dissolved organic carbon partition coefficients for nonionic organic chemicals. Environ Sci Technol 34:4663-4668.

$$k_{bl} = \frac{\nu_w^{1/2} u_*^{1/2}}{Sc^{2/3} y_0^{1/2}}$$

Where v_w is the kinematic viscosity of water (~0.01 cm^2/sec), u* is the friction velocity characterizing the shear stress at the sediment-water interface (typically, 1-5 cm/sec), y_0 is the hydrodynamic roughness of the sediment-water interface (typically 1-10 cm) and Sc is the Schmidt number, the ratio of kinematic viscosity of water to the molecular diffusion coefficient of the contaminant in water (of the order of 1000 for most contaminants in water).

Dispersivity, α - Dispersion is characterized by αU where U is the Darcy velocity. α is the order of the length scale of heterogeneities in the cap. In this version we employ a conservative estimate of dispersivity of 5% of the cap thickness. The Neuman[4] groundwater model of $\alpha=1.69(h_{cap}(\text{in m}))^{1.53}$ is employed except that α is not allowed to be less than 1 cm. Note that this is one of the most uncertain parameters in the simulation although it normally has little influence unless advection is strong.

Diffusion coefficient , D_1 –Diffusivity in cap layer is modeled as per Millington and Quirk[5] if granular (sand, gravel) or Boudreau[6] if consolidated sediment.

Millington and Quirk $D_{diff} = \varepsilon_1^{4/3} D_w$

Boudreau $D_{diff} = \dfrac{\varepsilon_1 D_w}{1 - \ln \varepsilon_1^2}$

<u>Output-Steady State Model (Contents of these cells should not be changed)</u>

Pore Water Concentration at Depth, C(z) – Model calculated steady state porewater concentration in porewater at the specific depth of interest, in µg/L

Solid Concentration at Depth of Interest, W(z) – Model calculated steady state bulk solid phase concentration in µg/kg

Average Bioturbation Layer Loading, (Wbio)avg – Model calculated steady state average bulk solid phase concentration in the biologically active zone, in µg/kg

Flux to Overlying Water Column, J – Model calculated steady state flux to overlying water, µg/m^2·yr

Cap-Bioturbation Interface Concentration, Cbio/C0 – Steady state porewater concentration at the cap bioturbation layer interface, in % of concentration in underlying sediment

Cap-Water Interface Concentration, Cbl/C0 – Steady state porewater concentration at the cap water

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[4] Neuman, S.P. 1990. "Universal Scaling in Geologic Media," Water Resources Research, 26(8):1749-1758.
[5] Millington, R.J., and Quirk, J.M. (1961) "Permeability of Porous Solids," Transactions of the Faraday Society, 57:1200-1207.
[6] Boudreau, B. (1997) Diagenetic Models and Their Implementation: Modeling Transport Reactions in Aquatic Sediments. Springer-Verlag, New York.

interface, in % of concentration in underlying sediment

Average Bioturbation Concentration, (Cbio)avg/C0 – Steady state average porewater concentration in the biologically active zone, in % of concentration in underlying sediment

Time to Containment Breakthrough, tadv/diff – Time before significant concentrations are expected in the biological active zone. Also the time after which the transient analytical model (2nd tab) may begin to overestimate concentrations in the biologically active zone. It indicates the approximate time before the concentration and flux at the top of the chemical isolation layer is 1% of what it is in the sediments.

$$t_{adv/diff} \approx \frac{1}{1/t_{diff} + 1/t_{adv}} \approx \frac{1}{16D_1/(R_1 h_{eff}^2) + U/(R_1 h_{eff})} \approx \frac{R_1 h_{eff}^2}{16D_1 + U h_{eff}}$$

Output - Transient Model (Transient Model Tab)

The model inputs summarized above are used to calculate key parameters for the transient model in the chemical isolation layer, i.e. the conventional sand layer as modified by the effective thickness of the active cap layer. These parameters include Peclet number (relating advection to diffusion, Dahmkohler number (relating reaction to diffusion), and a parameter u which is affected by both diffusion and advection. The final parameter needed for the model is the simulation time. The time until significant concentrations are noted in the biologically active zone is $t_{adv/diff}$. This would normally be the simulation time although if the the bioturbation rate in the biologically active zone (or migration rate through the conventional cap layer in the active layer model) is small or the concentration in that zone as predicted by the model at $t_{adv/diff}$ is small, the simulation time can be extended to give estimates of concentration in the capping isolation layer over a longer period of time. This may be especially important with an active sorbing layer in that the concentrations in much of the capping isolation layer are very small and essentially uniform for long periods of time after some penetration of contaminants are noted in the biologically active layer. If a longer simulation time it can simply be entered in the identified cell. The output from the simulation is shown on a figure showing both transient curves at various times and the long-time steady state curve for comparison. The results are also shown as concentrations (as the ratio of concentration to underlying sediment concentration) as a function of depth (in cm) and time. Note that the output will provide increased resolution in the sorbing active cap layer as appropriate.

Sensitivity Model Tab

The final tab in the spreadsheet model is designed to conduct sensitivity analyses on the steady state model. The tab does not include capabilities for conducting sensitivity analyses on the transient model. On this tab, the model parameters can be varied as desired to evaluate the output variables, for example concentration at a specific point of interest or in the biologically active zone. Columns B and C should not be changed. Column B is tied to the parameter values on the steady state conditions tab while column C is tied to column B. Column C can be copied and the values pasted in any number of additional columns and then values of selected parameters changed in those columns to allow parameter values to be changed.